Modeling induced seismicity due to fluid injection and withdrawal in deep boreholes: a Coulomb stress approach.

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ABSTRACT

Fluid injection and withdrawal in deep wells is a basic procedure in mining activities and deep resources exploitation, i.e. oil and gas extraction, geothermal exploitation, geothermal permeability enhancement and waste fluid disposal. All these activities have the potential to induce seismicity, as demonstrated by the 2006 Basel earthquake of magnitude ML=3.4. Despite several decades of experience, the mechanism of induced seismicity is not known in detail, preventing an effective risk assessment and/or mitigation. In this work, we give an interpretation of induced seismicity based on the computation of Coulomb stress changes resulting from fluid injection/withdrawal at depth, mainly focused to interpret induced seismicity due to Enhanced Geothermal System (EGS) reservoir stimulation. Seismicity is in fact, theoretically, more likely where Coulomb stress changes are larger. For modeling purposes, here we simulate the thermodynamic evolution of the system after fluids injected/withdrawn. The retrieved changes of pressure and temperature are subsequently considered as sources of incremental stress changes, which are then converted to Coulomb stress changes on favored faults, taking into account also the background regional stress. Numerical results are then applied to simulate the water injection used to create the fractured reservoir at the Soultz-sous-Forets (France) EGS site. For such simulation, we use both isotropic and non-isotropic permeability models, the last ones based on previous inference of this kind found in literature. The obtained results show that our approach provides a very good description of induced seismicity, and gives a natural explanation to the different impact, in terms of induced seismicity, respectively of fluid injection and fluid withdrawal. In particular, it accurately reproduces the location and mechanisms of induced seismicity at this and likely at the other EGS sites, thus representing a powerful tool for its interpretation and mitigation.

1. INTRODUCTION.

Geothermal systems represents a large resource that can provide, with a reasonable investment, a very high and cost-competitive power generating capacity. Considering also the very low environmental impact, their development represents, in the next decades, an enormous perspective (MIT Report, 2006). Despite this unquestionable potential, geothermal exploitation has been perceived till now as limited, mainly because of its dependance from several natural favourable conditions, like high geothermal gradients and high rock's permeability. In the last decades, a notable progress has been achieved with the Enhanced Geothermal Systems (EGS) (Portier and Vuataz, 2009), where massive fluid injection and withdrawal are performed to enlarge the natural fracture system of the basement rock. The permeability of the surrounding rocks results highly increased by pressurized fluids circulation and geothermal resources, in such way, become accessible in areas where deep reservoir exploitation, otherwise, could be not economically advantageous or even possible. Still problematic remains, however, most of the key technical requirements, and mainly the deep fluid injection at high pressure needed to create a permeable reservoir. This kind of procedure has the potential to induce seismicity that, although generally of very low magnitude, can attain sometimes considerable size, thus posing serious problems of acceptability. This was the case of the 2006 M=3.4 earthquake induced in the Basel city (Swiss), with the consequent early termination of the EGS project (Haring et al., 2008; Ripperger et al., 2009).

2. METHOD

Our method of analysis consists of a two-step procedure. In the first step, injection or withdrawal of water is simulated (Pruess, 1991). The modeled 3D physical domain and the imposed initial conditions are shown in Fig.1.

Water at ambient condition is withdrawn or injected at a chosen rate in a point located at -5 km depth. In such a way we obtain the pressure and temperature changes at each point in the medium, subsequently considered as mechanical sources, heterogeneously distributed in the whole discretized Volume, which generate an incremental stress tensor field estimated by using the Comsol Multiphysics finite element code (Troiano et al., 2011). Once the complete field of stress changes is computed, Coulomb stress changes on a given fault plane in the volume are computed on the favorably oriented fault planes, i.e. on which the total Coulomb stress, including the tectonic stress plus the incremental stress due to withdrawal/injection of water reaches its maximum value (Troise et al., 1998).

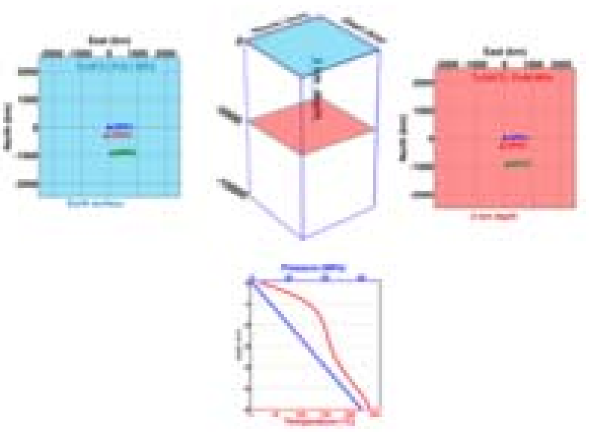

Figure 1: Sketch of the simulation volume. GPK1, GPK2 and GPK3 well positions projected on the Earth surface are detailed. On the center the whole analyzed volume is shown. Blu plane (on the left) represents the Earth surfaces and red plane (on the right) represents the injection plane at 5 km depth. Intial pressure (blue line) and temperature (red line) condition are reported on the bottom.

We have applied our procedure for two distinct cases:

a) a continuous water injection (and withdrawal) at fixed rate of 50 kg/s in a homogeneously permeable medium. Effects in terms of Coulomb stress changes are shown in Fig.2.

b) a simulation of a real injection experiment. For the case b, we reproduce the joint stimulation of two distinct wells (named GPK2 and GPK3) realized in the Soultz.-sous-Forets geothermal site and accurately reported in Baria et al. (2004). The simulated injection history is shown in Fig.3.

Results in terms of over-pressurization and Coulomb stress changes over the whole volume are shown in Fig.4.

Comparison between Coulomb stress changes and induced seismicity observed at Soultz-sous-Forets is also reported along an horizontal plane passing for the injection point, in Fig.5.

In both cases, a background tectonic stress coherent with the one estimated for the Soutz-sous-Forets area is imposed.

We propose, in such a way, a procedure to estimate how the potential for failure in geothermal areas changes due to well stimulation.

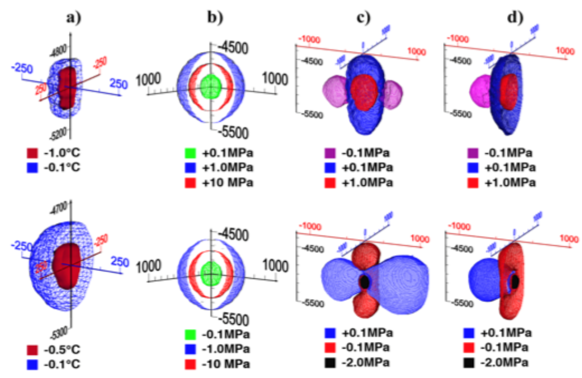

Figure 2: Effects related to injection (upper) and withdrawal (lower) of 50 kg/s of water, at 5 km of depth, in a homogeneous medium with permeability 10-16 m2 are shown. In particular are reported a) temperature changes b) pressure changes and maximum Coulomb stress changes sliced on a c) xz plane and d) yz plane.

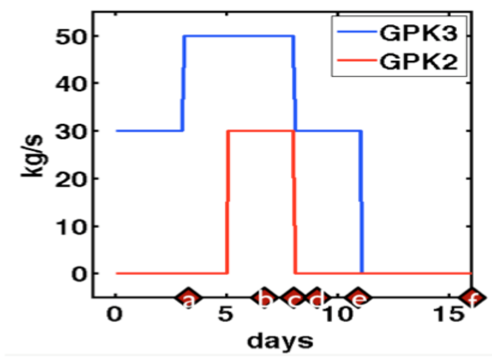

Figure 3: Simplified stimulation functions for GPK2 and GPK3 Soultz-sous-Forêts wells, representing the rates of injected water. Letters from a to f refer to the times of the stimulation cycle shown.

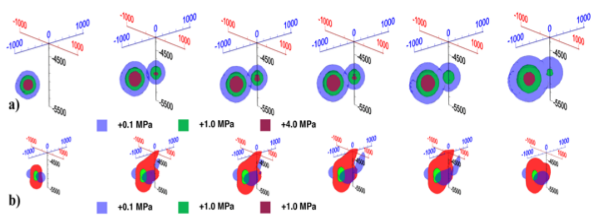

Figure 4: Estimated pressure changes (a) and maximum Coulomb stress changes (b) for the different phases of the injection experiment described in Figure 3. The distinct columns are related to time from a to f.

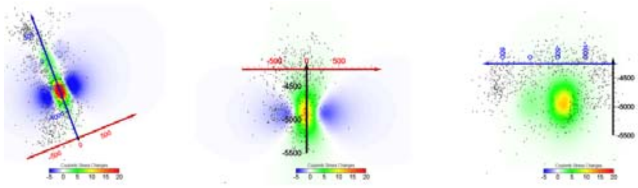

Figure 5: Results (projected on three orthogonal slices) for maximum Coulomb stress changes at the end of the injection cycle of Fig.3. The x axis of the reference system is along the direction passing between the two wells. Coulomb stress changes are also compared with seismicity occurred in the relative periods. Note the good agreement between positive stress changes and seismic areas.

3. CONCLUSION

Firstly, we note from fig.2 that water injection is much more efficient to generate high Coulomb stress changes and then stimulate seismicity, with respect to water withdrawal. This effect, well recognized in mining practice, occurs because water injection increases in general pore pressure and hence Coulomb stress, so intrinsically favouring seismicity, whereas water withdrawal decreases them. However, it must be noted that pressure changes convert in Coulomb stress changes in a complex way, so that also withdrawal generates at some places positive Coulomb stress changes, even if generally lower than injection case, thus stimulating seismicity.

In the case of Soultz-sous-forets simulations, our results show a very good agreement between modeled maximum Coulomb stress changes and observed seismicity, as evident in fig.5. In particular the near N-S distribution of the seismic events is retrieved, with the correct alignment along the two wells. Noteworthy, at time a, after 4 days of continuos water injection just in the GPK3 well, while the overpressure pattern still retains a spherical symmetry, the Coulomb stress changes already show an elongated pattern. Being the GPK2 well still shut off, this lack of simmetry can be related just to the pre- existing loading of the regional stress field. On other hand, at the end of our simulation, at time f, this elongation effect of the Coulomb stress changes pattern results enhanced and a similar behavior appears also in the Pressure changes (fig.4). This indicates that the N-S distribution of the seismic cloud results enhanced by the joint stimulation effects. The pressure front, and the associated increase of the Coulomb stress levels, continue to expand also after both wells are shut off, and this effect matches with the persistency of induced seismicity and the peripheral distribution of the events, formerly associated (Baria et al., 2004) to a buoyancy effect. We show in figures such agreement only for initial and final stimulation times, although it remains optimal also in the intermediate ones.

On the grounds of our results, it appears that the main causes of induced seismicity during stimulation are the Coulomb stress changes generated by water injection. Actually, this model, besides constituting an important step towards interpretation and mitigation of induced seismicity, could be equivalently used for a better planning of reservoir stimulation as well as to forecast the areas of higher likelihood for induced seismicity.

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